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Reconfigurable Supply Chain: The X-Network

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Abstract

The research on supply chain (SC) digitalization, resilience, sustainability and leagility has remarkably progressed, most of it focused on the individual contributions of these four major determinants to the firm's profitability and competitiveness. Though, there appears to be a lack of conceptual guidance surrounding their roles and interplays as an integrity. We hypothesize that such an integrity frames a new kind of SC networks, or even a new understanding of the SCs. We theorize a new notion - a Reconfigurable SC or the X-network – that exhibits some crucial design and control characteristics for complex value-adding systems in highly vulnerable environments. Utilizing abductive approach and a systematic bibliometric co-occurrence analysis of 1383 articles along with tertiary studies, we review and investigate contextual factors of designing the X-networks. We propose respective frameworks and discuss the implementation principles and technologies at the macro and micro levels. Two novel concepts – dynamic SC meta-structures and dynamic autonomous services – are introduced and formalized. Distinctively, we go beyond the existing knowledge to predict proactively the future directions in the reconfigurable SCs. Alike our results can be of value for decision-makers to decipher systematically the chances and barriers in contemporary SC transformations.

Keywords: Supply chain management; Supply chain resilience; Sustainable supply chain; Industry 4.0; Agility; Leanness; Ripple effect; Digital twin; Reconfigurable supply chain.

1. Introduction

At the times of climate changes, frequent natural disasters, digitalization and cyber-physical systems, companies undergo transformations of their supply chains (SC) and have a common question to ask: how to improve SC profitability and competitiveness while being environmentally friendly and technologically advanced? Some practical examples of such novel concepts follow. Audi smart factory in Baden-Württemberg implements a highly flexible assembly system based on the use of automated guided vehicles. Contrary to the traditional assembly systems with fixed layouts and process designs, the Audi smart factory allows for highly flexible process design and sequencing of production orders in order to achieve the highest degree of the product individualization while maintain the manufacturing efficiency (Audi 2019). MindSphere (a manufacturing platform of Siemens) is cloud-based and represent an open operating system on the basis of Internet-of-Things (IoT) where products, plants, systems, and machines are connected with each other to enable the usage of data generated by the IoT with advanced analytics in schedule optimization (Siemens 2018). UPS and SAP developed a joint technology which allows UPS to manufacture items using 3D printing directly at the distribution centers (UPS 2018). IBM and Maersk are collaborating to create trust and transparency in global SCs using Blockchain (IBM 2017). Unilever (2020) re-designed packaging processes in the global SC from the viewpoints of the circular economy. Adidas Speedfactory makes it possible to increase the responsiveness of the SCs while contributing to sustainable manufacturing by utilizing new digital technologies, i.e., additive manufacturing (Adidas 2020).

In this study, which is designed as a conceptual viewpoint paper, we hypothesize that some of this success is attributable to the reconfigurability of the SCs. Indeed, recent literature episodically debated about the SC reconfigurability. For example, Cândido et al. (2009) elaborated on the information, service-oriented infrastructure of the reconfigurable SCs from the position of the embedded systems. Ivanov et al. (2009) proposed a control framework for SC reconfigurability. Malladi et al. (2020) studied the utilization of transportable modular production capacity along with the inventory control to increase dynamic SC reconfiguration. Extant literature in the logistics and transportation area revealed the potentials of risk pooling and lateral transshipments as examples of SC reconfiguration (Zhao et al. 2016, Arikan and Silbermayr 2018, Firoozi et al. 2019). Some further specific mentioning of the reconfigurable SCs can be found in (Nyaka and Mpofu 2013, Pattanaik et al. 2020). None of these studies, however, have provided a comprehensive framework of the reconfigurable SC underpinned by a solid multi-methodological base and multi-disciplinary analysis – a distinct and substantial contribution made by our study.

In our understanding, *a Reconfigurable SC (RSC) is a network designed in a cost-efficient, responsive and resilient manner that is increasingly data-driven and dynamically adaptable and capable for rapid structural changes in the physical and cyber spaces, by rearrangement and reallocation or change of its components in order to quickly adjust supply and production capacities and functionality in line with the sustainable developments and in response to sudden changes in markets or upstream disruption risks.*

In the title of this paper, a generic “X” is used to designate the new generation of the SCs – the reconfigurable networks that are evolving through a mutual enhancement of various core concepts of SC systems that are in use in the literature and industry. Those concepts for the transformations towards the RSC are multiple and include but are not limited to Agile SC, Lean SC, Digital SC, Sustainable SC, and Resilient SC (Altay et al. 2018, Blackhurst et al. 2011, Brandenburg and Rebs 2015, Choi et al. 2018, Das et al. 2006, Dolgui et al. 2018, Dubey et al. 2015, Govindan et al. 2016, Hosseini et al. 2019a, Ivanov 2018b, Ivanov and Dolgui 2019, Ivanov et

al. 2019b, Tang and Veelenturf 2019, Wamba et al. 2017). The agile, lean, digital, resilient and sustainable SC concepts, and their combinations cover a large variety of features which are considered in the contemporary SC transformations. In particular, further improvements in SC management are seen in literature in light of the following integrated frameworks:

- combinations of lean, agile and digital for increasingly data-driven market responsiveness (Dubey et al. 2018, Gunasekaran et al. 2018, Ivanov and Dolgui 2019, Zhong et al. 2017) implemented as, e.g., modular storage capacity (e.g., smart lockers) and leagile production capacity (e.g., 3D printers);
- efficient and resilient supply chains (so called LCN – low-certainty-need SCs) with the advantages of both lean and risk-resistant/recoverable SCs (Ivanov and Dolgui 2019);
- combinations of sustainable and resilient (Amindoust 2018, Ivanov 2018a, Fahimnia et al. 2018, Fiksel 2003, Ramezankhani et al. 2018);
- digital technology for sustainability (Papadopoulos et al. 2017, Manupati et al. 2020);
- combinations of digital and resilient to support the data-driven decision-making support (Cavalcante et al. 2019, Choi et al. 2017, Dubey et al. 2019b, Ivanov 2017b, Ivanov et al. 2019b,c, Ivanov and Dolgui 2020)

From literature analysis, it becomes evident that there are multiple intersections of several SC concepts which have partially been uncovered in literature. Though, these intersections are scattered over literature and have not brought into an integrity so far – a substantial and distinctive contribution made by our study. As such, our analysis builds upon three specific research questions (RQ):

RQ1. What is the state-of-the-art in the existing literature related to Reconfigurable SC?

RQ2. What are the contextual factors forming the research on Reconfigurable SC and opportunities for further investigations?

RQ3. What are the principles and technologies to implement the Reconfigurable SC?

Distinctively, we aim to go beyond the existing knowledge and to predict proactively the promising directions in future research on RSC. Although digitalization, resilience, sustainability and leagility have evolved from emergent topics to major determinants in the SC management and research, attention has been yet mostly focused towards their individual contributions to the firm's profitability and competitiveness. There appears to be a lack of conceptual guidance surrounding the roles and interplays of these four major determinants in providing an integrity of a new kind of SC networks.

For the first time, our study hypothesizes that digitalization, resilience, sustainability and leagility frame the pillars of a new concept, or even a new understanding of the SCs. We theorize and conceptually develop a new notion - a Reconfigurable SC or the X-network – that exhibits some crucial characteristics to design and control the SCs and their meta-structures in highly dynamic and vulnerable environments. We review and investigate contextual factors of designing the X-network proposing a respective framework along with the implementation technologies and principles at the macro and micro levels. Utilizing a methodology based upon an abductive approach and systematic bibliometric co-occurrence analysis of 1383 articles along with a tertiary study towards conceptual theory building, we show how digitalization, resilience, sustainability and leagility can be positioned self-contained in their singularity and mutually enhanced by each other in their integrity within the RSC. Moreover, we introduce two novel concepts within the RSC that operate in highly vulnerable environments, i.e., dynamic SC meta-structures and dynamic autonomous services. We present and discuss these new concepts.

The outcomes of this research can be used to advance the researchers’ perspectives on the future developments in the SC management theory. Alike, our results can be of value for decision-makers to decipher the chances and barriers in the process of contemporary SC transformations systematically.

The rest of this study is organized as follows. Section 2 presents our methodology. In Section 3, we elaborate on the RSC macro- and micro frameworks. Implementation principles and technologies are discussed in Section 4. The concepts of the reconfigurable meta-structures and dynamic autonomous services are introduced and formalized in Section 5. Section 6 builds the discussion around the future research agenda. The paper is concluded in Section 7 by summarizing the major findings and delineating future research perspectives.

2. Methodology

We utilize a methodology based upon an abductive approach supported by a systematic bibliometric search in SCOPUS database and a subsequent co-occurrence analysis of the literature reviews on SC digitalization, resilience, sustainability, and leagility. We believe that the use of the systematic literature analysis validates our abductive approach as it links to primary and secondary data from the bibliometric analysis to our concepts. Fig. 1. depicts the logic of our research.

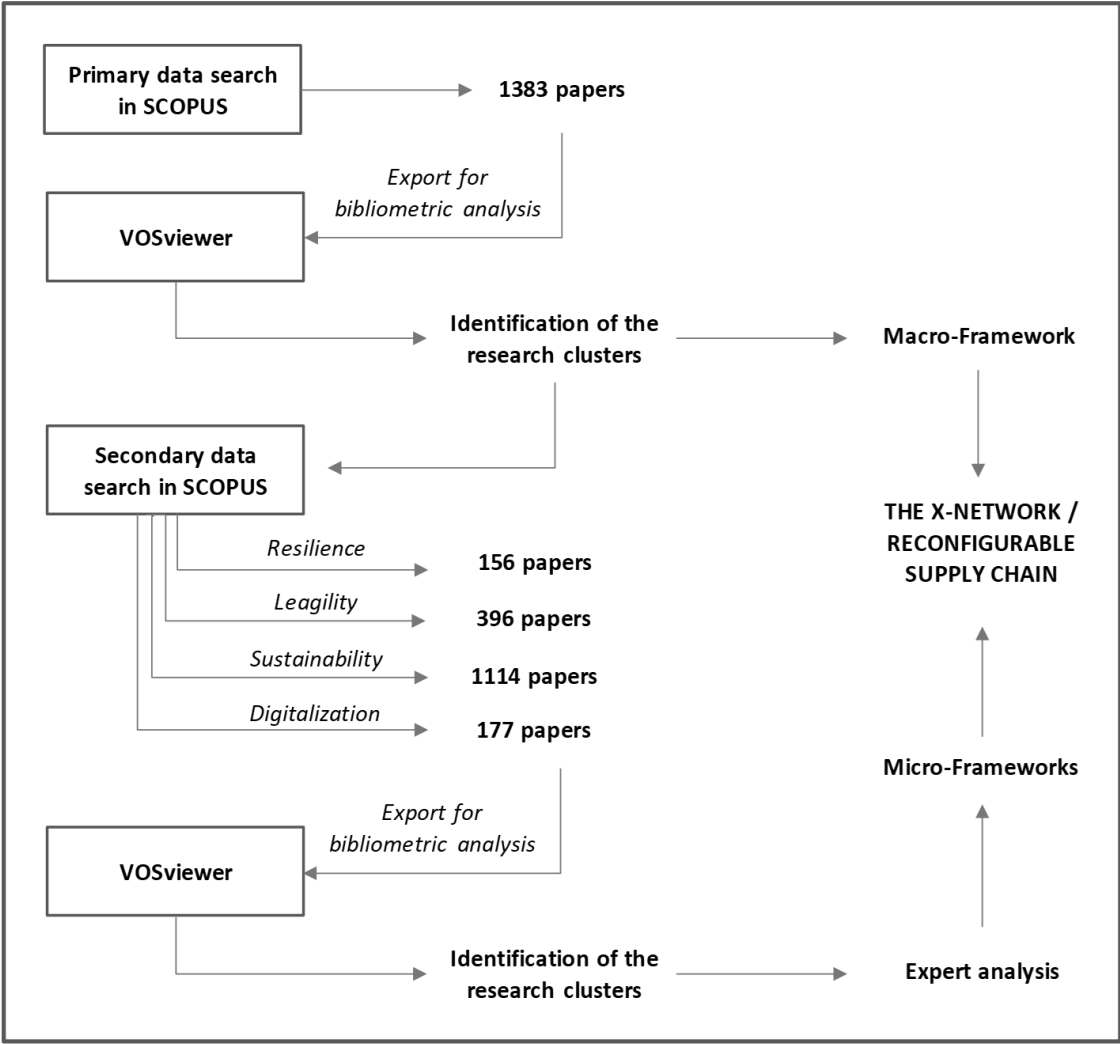


Fig. 1. Research methodology

To start with, and as an analogy to the manufacturing systems domain and reconfigurable manufacturing systems (RMS) in particular, we considered Reconfigurability as the central feature of the X-networks. In the first paper on RMS, Koren et al. (1999) underline that in order “to survive in this new manufacturing environment, companies must be able to react to changes rapidly and cost-effectively.” They define that “A Reconfigurable Manufacturing System (RMS) is designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements.” According to Dolgui and Proth (2010), “RMSs are designed to permit quick changes in the system configurations, their machines and controls in order to adjust to market changes.” Mehrabi *et al.*, 2002 define that a “reconfigurable manufacturing system is designed for rapid adjustment of production capacity and functionality in response to new circumstances, by rearrangement or change of its components.” Moreover, Battaia et al (2020) show that RMS can be considered as a new way to manage manufacturing system sustainability.

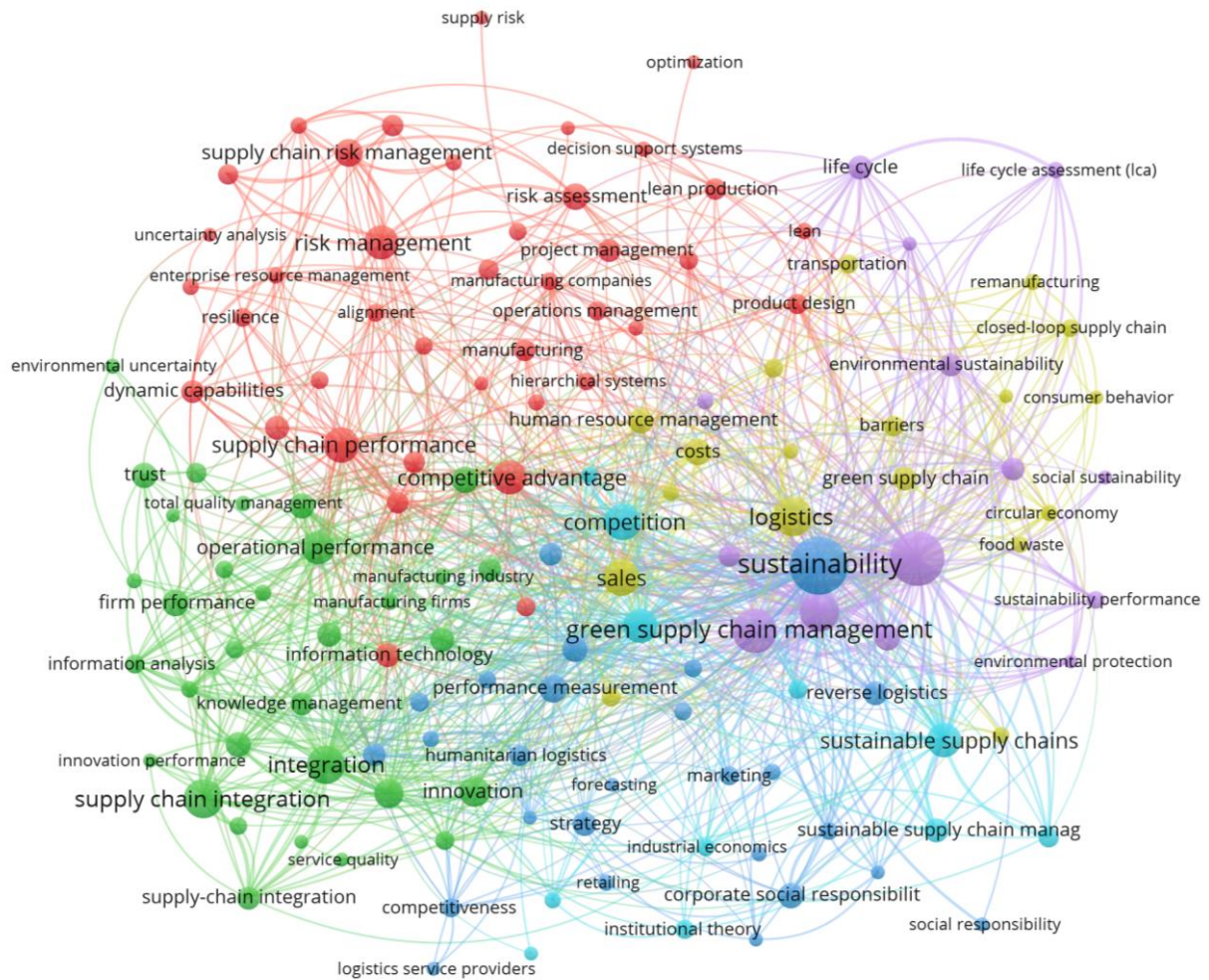
Having these definitions in mind, the first step in our study was to derive the features belonging to the Reconfigurable SC. In doing that, we performed a SCOPUS search blended with the subsequent analysis with VOSviewer co-occurrence Analysis (VCA; www.vosviewer.com) (van Eck and Waltman, 2009). This methodology has been successfully used, e.g., by Ali and Golgeci (2019) stating that “... to retrieve the relevant articles in the area, VCA helps to objectively and algorithmically identify and aggregate the key terms into distinct clusters, representing the main research domains and directions of the future research in the field.”

Second, we analysed the clusters and derived four major pillars of a RSC: resilience, sustainability, leagility, and digitalization. Third, we repeated the procedure of the first step again with SCOPUS and VOSviewer in the form of several tertiary studies for each of the clusters by analyzing the literature reviews and the surveys in each of the clusters respectively. Then we read the selected key (i.e., the most referenced ones) articles within each cluster. Finally, we used findings from VCA results and the subsequent literature reviews to build a macro- and micro frameworks of the X-network and particular suggestions for further research.

3. The X-Network: Building the macro and micro frameworks

3.1. Macro-framework

For building the macro framework of the X-network, the articles were searched by applying multiple keywords related to SC reconfigurability (following the keywords from the RMS definitions given in Section 2) including “supply chain” AND “structural change” OR “reconfiguration”, OR “response”. The iterative search process yielded 1383 articles by limiting the search scope to the fields “Business, Management and Accounting and selecting peer-reviewed journals only (which warrants that a literature review maintains a certain level of quality and reliability as pointed out by (Tang and Musa 2011)). Within this sample, VOSviewer Co-occurrence Analysis (VCA) and its clustering functions have been used, which help compute similarities between key terms given their association strength and a weighted sum of squared distance (van Eck and Waltman, 2009; Ali and Golgeci 2019). The result is presented in Fig. 2.



Digitalization	Leagility	Resilience	Sustainability
information technology; innovation; integration; performance; supply chain integration; trust	agile; costs; lean; manufacturing; sales; transportation	decision-support system; risk assessment; risk management; SC performance; supply risk; uncertainty analysis;	circular economy; closed-loop SC; environmental protection; green SC management; humanitarian logistics; sustainable SC;

Fig. 2 Bibliographic data map

The keyword analysis (minimum keyword occurrence is 10) along with the network and overlay visualization lead us to four concepts relevant to the macro-framework of RSC: resilience (red), sustainability (blue/purple), leagility (yellow), and digitalization (green). On the basis of the keyword analysis in the clusters, textual analysis and reading selected key articles, the macro framework “X-Network” has been built as presented in Fig. 3.

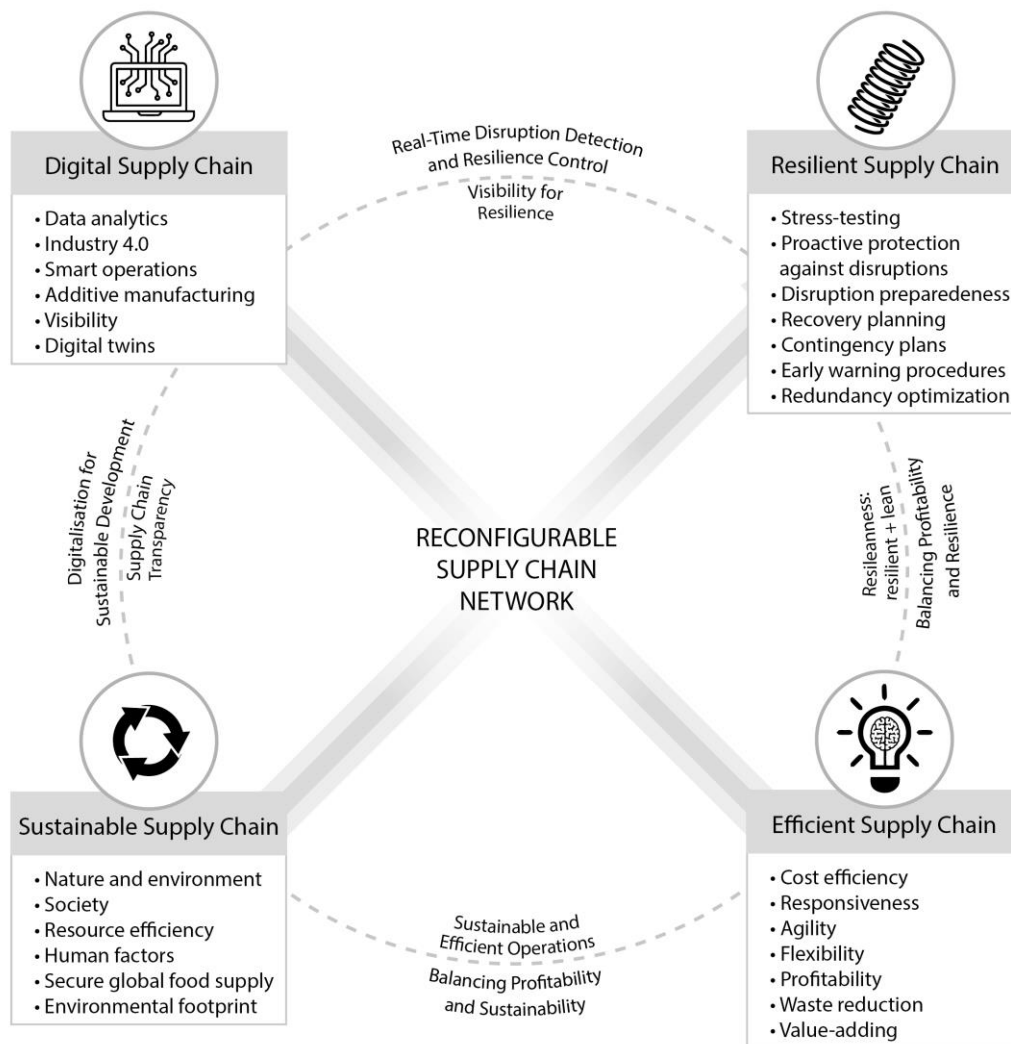


Fig. 3. The X-Network macro-framework: Design of the Reconfigurable SC

The reconfigurable SC exhibits for distinctive features. The *first* feature of the X-network is framed by the resilience. Hosseini et al. (2019a) defined resilience as “the network capability to withstand, adapt, and recover from disruptions to meet customer demand and ensure performance”. Literature allows identify several contributions of resilience to SC reconfigurability. Generically, these contributions can be classified into proactive and reactive areas. At the proactive stage, i.e., in the pre-disruption decision-making, recent research suggested methods and models to perform stress-testing of SCs for disruptions in the upstream and downstream parts, to improve protection against disruptions, to increase disruption preparedness (Blackhurst et al. 2011, Brandon-Jones et al. 2014, Chen and Miller-Hooks 2012, Chopra and Sodhi 2014, Cui et al. 2010, He et al. 2018, Lückert et al. 2017, Macdonald et al. 2018). Novel insights have also been obtained in the area of SC risk propagation and ripple effect control (Ivanov et al. 2014, Garvey et al. 2015, Ivanov et al. 2017a, Dolgui et al. 2018, Levner and Ptuskin 2018, Scheibe and Blackhurst 2018, Hosseini and Ivanov 2019, Ivanov et al. 2019a, Kinra et al. 2019, Li et al. 2019, Mishra et al. 2019, Sinha et al. 2019). Contingency plans and redundancy optimization build another important knowledge area at the proactive stage (Hu et al. 2013, Ivanov et al. 2014b, Ivanov et al. 2017a, Ivanov 2018b, Lückert et al. 2019, Pavlov et al. 2019a,b, Yildiz et al. 2016). The reactive stage analysis is devoted to recovery planning (Dolgui et al. 2019a, Dubey et al. 2019a, Ivanov et al. 2018, Nguyen and Nof 2019, Sodhi and Tang 2012, Paul et al. 2014, Zhao et al. 2019).

It can be observed from Table 1 that the RSC comprehensively combines elements driven from lean, agile, resilient, sustainable and digital SCs. In this integrity, the RSC is a unique macro-framework which is worth being analysed more detailed at the micro-level.

3.2. Micro-Framework

In this section, we elaborate on each of the four RSC pillars by combining the tertiary co-occurrence analysis with a manual and deeper investigation into the co-citation clusters and an expert identification of the most recent relevant papers. In this section we look at more details and arrive at the concrete concepts, principles and technologies that can be used to frame the RSCs and represent in their integrity the micro-framework of the X-Network. Moreover, our special interest in this section is to derive intersections between the four pillars of the X-network macro-framework at the micro-level.

3.2.1 Tertiary study 1: SC resilience

We performed a SCOPUS search in order to analyse surveys on SC resilience using the following combination of keywords: “SC resilience AND survey OR literature review”. 156 documents have been identified. The most common keywords have been SC disruptions, preparedness, vulnerability, complexity, robustness, dynamics, and risk assessment. The result of the co-occurrence analysis is shown in Fig. 4.

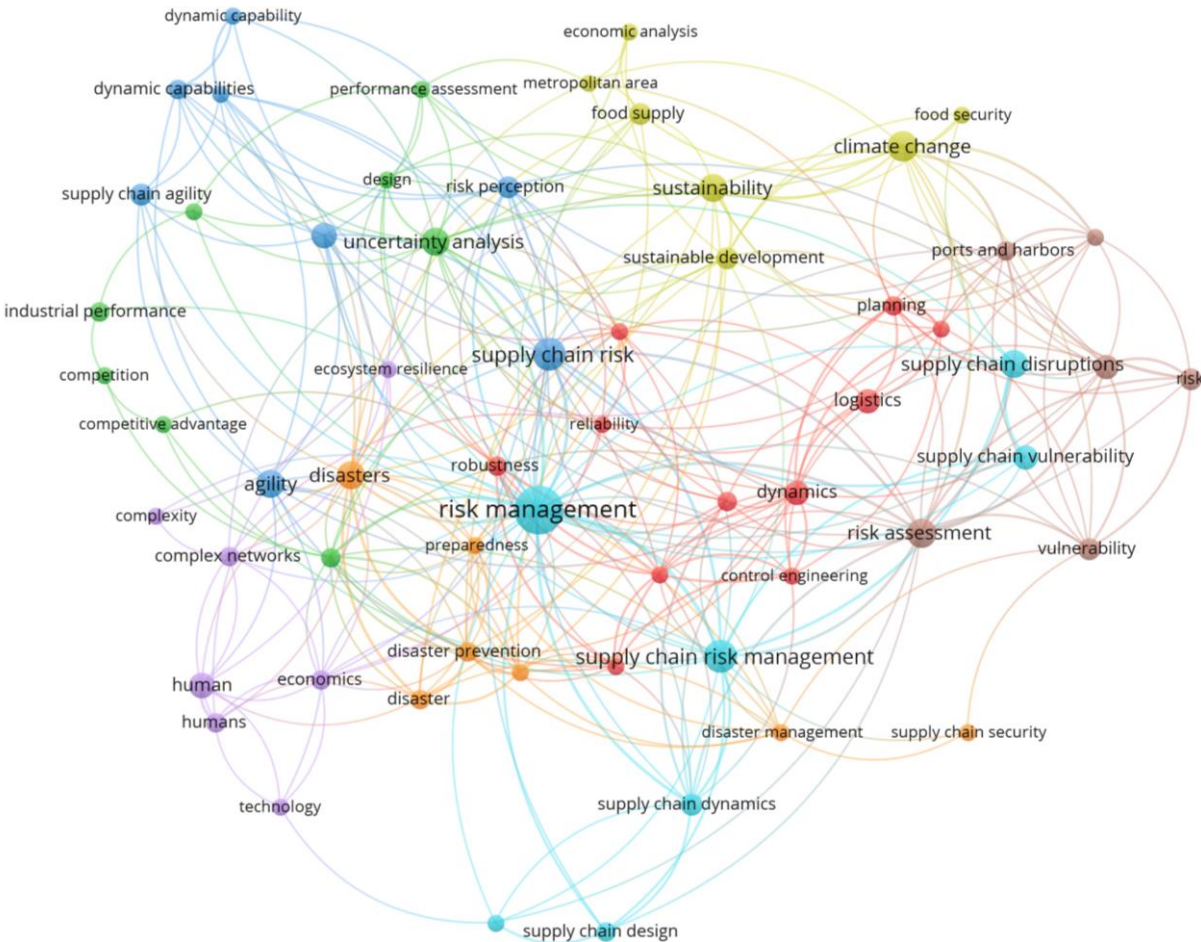


Fig. 4. The result of the co-occurrence analysis in the area “SC resilience”

Interestingly, Fig. 4 shows that SC resilience keywords are intersecting with leagility, sustainability and digitalization, e.g., agility, information management, sustainability. The SC resilience has been coined in literature by Blackhurst et al. (2005, 2011), Christopher and Peck (2004) and

Sheffi and Rice (2005) being accompanied by a visible and important research stream of SC risk management Kleindorfer and Saad (2005), Tang (2006), Tomlin (2006), Kull and Talluri (2008), Sawik (2011). A number of remarkable reviews on SC resilience and risks has been published in recent years (Ali and Golgeci 2019, Bier et al. 2019, Ho et al. 2005, Hosseini et al. 2019a, Melnyk et al. 2014, Pettit et al. 2019, Snyder et al. 2016, Tukamuhabwa et al. 2015, to name a few).

The literature analysis along with the VOSviewer results allow identify several intersections of SC resilience with leagility and sustainability. Less attention has been paid to the interface of resilience and digitalization. The first studies in this area (Choi et al. 2017a,b, Cavalcante et al. 2019, Dubey 2019a, Ivanov et al. 2019b, Ivanov and Dolgui 2020) showed numerous ways of improving SC resilience by digital technologies using data analytics, digital twins and block-chains. We refer to this stream as a promising research avenue.

The SC resilience research can be classified into structural variety and operational redundancy. Structural variety refers to the semantic level of analysis (Ivanov and Dolgui 2019). At this level, the research has been focused around the structural SC design properties, complexity roles and identification of critical nodes in the supply base (Adenso-Diaz et al. 2018, Ambulkar et al. 2015, Basole and Bellamy 2014, Bode and Wagner 2015, Chen et al. 2017, Garvey et al. 2015, Gao et al. 2016, Demirel et al. 2019, Ivanov et al. 2010, Ivanov and Arkhipov 2011, Ivanov et al. 2016, 2017b, Ivanov 2018b, Kim et al. 2015, Levalle and Nof 2017, Mizgier et al. 2017, Nair and Vidal 2011, Ojha et al. 2018, Pavlov et al. 2018, Snoeck et al. 2019, Tan et al. 2019, Zhao et al. 2011, Zhao and Freeman 2018). Robustness, reliability and resilience analysis of the SCs also belong to the structural level. The major insights in this area pertain to building structural variety, redundancy, segmentation and sustainability to enable SC robustness and resilience.

The studies on the operational redundancy build their arguments around capacity and inventory reservations as well as back-up suppliers to cope with SC disruptions (Behzadi et al. 2018, Chen et al. 2011, Lücker et al. 2017, 2019, Hosseini et al. 2019b, Ivanov and Rozhkov 2017, Ivanov 2019a, Paul et al. 2019, Paul and Rahman 2018, Sawik 2013, 2016, 2017, 2019, Schmitt et al. 2017, Song et al. 2018, Spiegler et al. 2012, 2016, 2017, Yin and Wang 2018, Yoon et al. 2016, 2018a,b). Some studies extended the operational discussion towards the product substitution and process/product modularity as mitigation and recovery policies (Lu et al. 2011, Gupta and Ivanov 2019). In addition, a few studies investigated structural and operational dynamics in the SC in an integrated manner (Dolgui et al. 2019a, Ivanov et al. 2018b, Ivanov and Sokolov 2019, Ivanov 2019b).

Ivanov and Dolgui (2019) point to several research gaps in the SC resilience area as follows: “First, structural SC design patterns need to be identified that allow for both efficient robustness and recoverability. Second, process flexibility policies need to be analysed which enable the reduction of disruption-driven process changes and efficient SC recovery. Finally, at the control level, the efficient usage of parametric redundancy and the development of reactive control policies are also research gaps that drive the pursuit to establish the LCN SC framework.” Note that LCN SC is the acronym of the Low-Certainty-Need Supply Chain.

3.2.2. Tertiary study 2: SC lean and agility

We performed a SCOPUS search in order to analyse surveys on SC leagility using the following combination of keywords: “SC lean OR SC agile AND survey OR literature review”. 396 documents have been identified. The most common keywords have been agility, agile manufacturing system, agile SC, lean manufacturing, lean thinking, just-in-time. The result of the co-occurrence analysis is shown in Fig. 5.

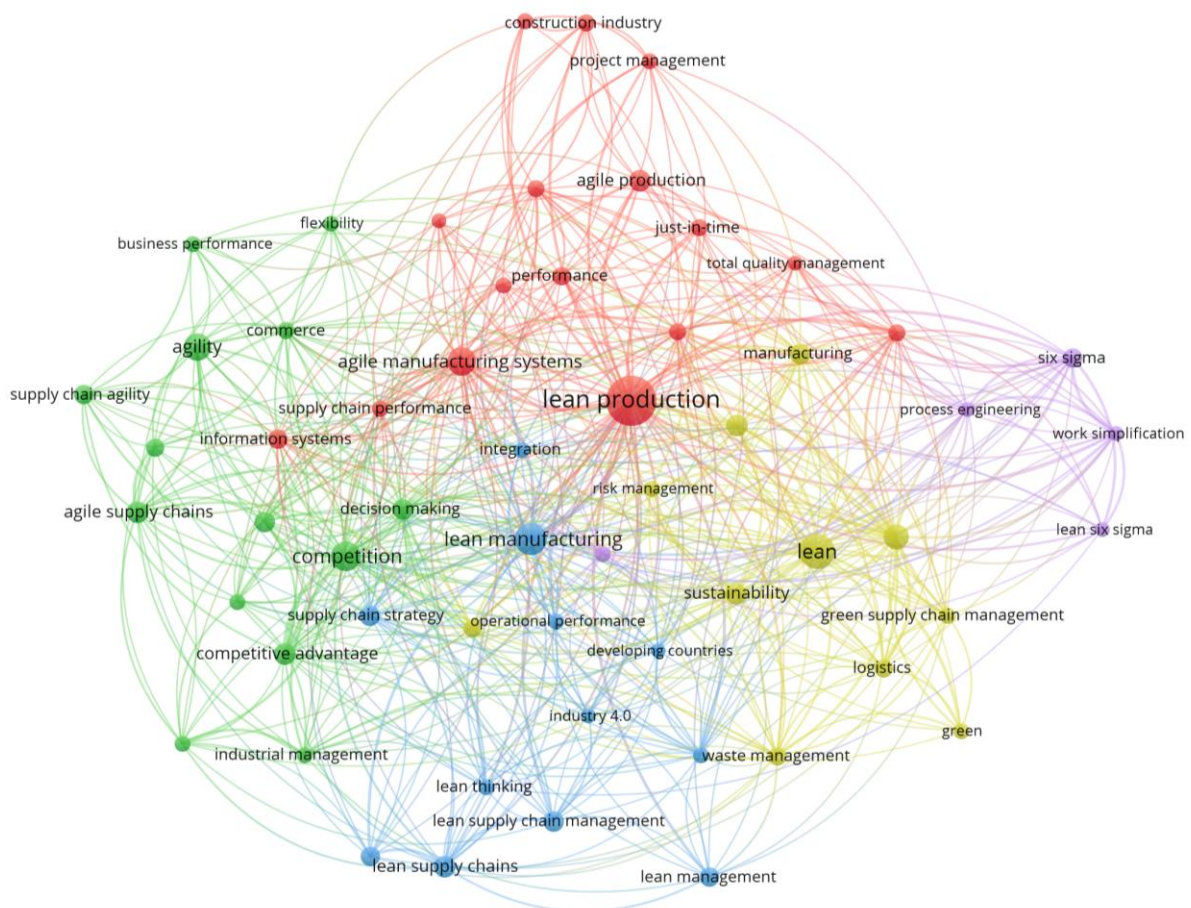


Fig. 5. The result of the co-occurrence analysis in the area ‘‘SC leagility’’

Interestingly, Fig. 5 shows that SC leagility keywords are intersecting with resilience, sustainability and digitalization, e.g., information management, information systems, Industry 4.0, risk assessment, risk management, sustainability, sustainable development, green.

SC agility has gained significant attention in last decade following the work by Lee (2002, 2004). Recently, Eckstein et al. (2015), Dubey et al. (2018) and Fadaki et al. (2020) have attempted to explain SC agility using contingent resource based view and dynamic capability view. Dynamic capabilities support enterprises to improve the profits by managing firm’s agility and leanness in an uncertain environment (Lawson and Samson 2001; Altay et al. 2018). Hasegan et al. (2019) argue that balancing the magnitude of leanness and agility could be a predictor of firm’s performance. These results have been echoed by Kumar et al. (2018) that took substantiated an alignment between lean an agile as one of the major determinants in improving SC performance. Moreover, they build up a link towards sustainability.

Alike the Kumar’s et al. (2018) paper, the intersections of leagility with resilience, sustainability and digitalization can be episodically found in literature. Sawhney (2006), Altay et al. (2018), Carvalho et al. (2012), Dubey et al. (2019b), Ivanov et al. (2018a) organized a debate around the intersections of flexibility, agility and uncertainty and developed the discussion towards the roles of agility and flexibility in achieving SC resilience. Fahimnia et al. (2014) and Dubey et al. (2015) pointed to empirically revealed intersections of the leagility and sustainability. Gunasekaran et al. (2016, 2018) focused the discussion around the interfaces of agility and digital technologies with a specific focus on big data. Ivanov and Dolgui (2019) developed the ‘‘Low-Certainty-Need (LCN)’’ framework that combines lean and resilient towards a new concept – the resileanness.

Their study also points to the practical ways of the realization of leagile principles using modularity, process flexibility, learning, transparency/blockchain, and structural diversity.

3.2.3. Tertiary study 3: Sustainability

We performed a SCOPUS search in order to analyse surveys on SC sustainability using the following combination of keywords: “SC sustainability AND survey OR literature review”. 1114 documents have been identified. The most common keywords have been SC disruptions, preparedness, vulnerability, complexity, robustness, dynamics, risk assessment. The result of the co-occurrence analysis is shown in Fig. 6.

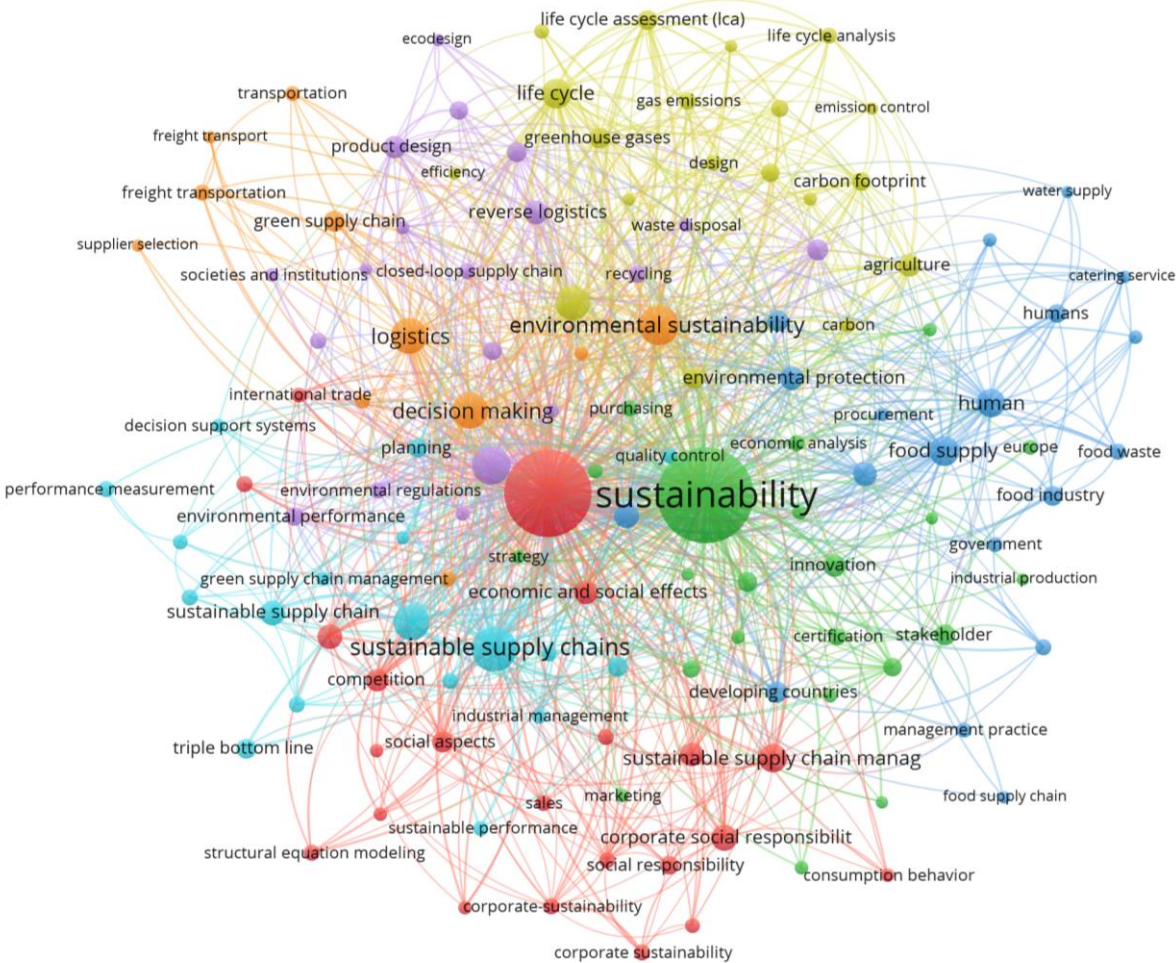


Fig. 6. The result of the co-occurrence analysis in the area “SC sustainability”

Interestingly, Fig. 6 shows that SC sustainability keywords are intersecting with resilience and digitalization, e.g., agility, information management, information systems, risk assessment, risk management. However, no intersection with leagility can be observed despite of some visible studies in this area (e.g., Fahimnia et al. 2014, Jabbour et al. 2018, Baumer-Cardoso et al. 2020) exist in this area. Amindoust (2018), Fahimnia and Jabarzadeh (2016), Fahimnia et al. (2018), Fiksel (2003), Giannakis and Papadopoulos (2016), Gaur et al. (2019), Ivanov (2018a), Papadopoulos et al. (2017) elaborate on the intersections of sustainability and resilience pointing to the structural dynamics which stems from the transformations of the SCs. Luthra et al. (2019) and Manupati et al. (2019) contribute to understanding of how digital technology impacts the SC sustainability.

The intersections of the SC digitalization with leagility, sustainability and resilience have also been noted in literature. Recent studies by Baryannis et al. (2019), Dubey et al. (2019b), Ivanov et al. (2019a,c), Schlüter et al. (2017) revealed several inherent features of the digital SC which can be utilized in managing SC risks and resilience. More specifically, disruption detection, real-time disruption impact analysis, early-warning systems and recovery learning belong to the new decision-making qualities that can be added by the utilization of the digital technology. To summarize, a digital SC is characterized by information feedbacks, coordination, learning, and transparency. All these features are interlinked with resilience, sustainability and leagility and frame a principally new research area.

3.2.5. The micro-framework of the X-Network

In this section, we recapitulate the individual micro-frameworks of SC resilience, sustainability, leagility and digitalization into a generic micro-framework of the X-network (Fig. 8).

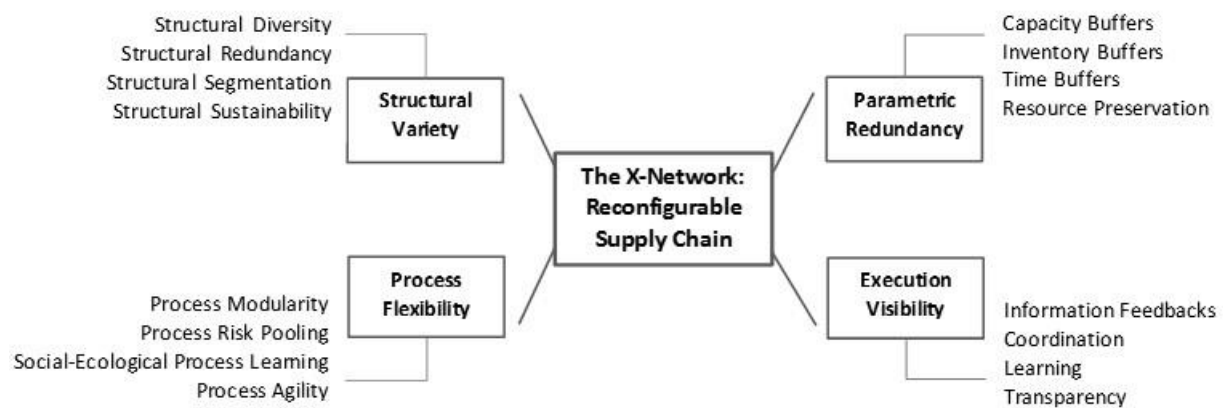


Fig. 8. Micro-framework of the X-Network: implementation of the Reconfigurable SC

The micro-frameworks of the reconfigurable SC offer concrete implementation methods and areas. The variety of the principles, model and methods in each of the individual resilience, sustainability, leagility and digitalization micro-frameworks are brought into a generic picture (Fig. 8) that is comprised of the structural variety, process flexibility, parametric redundancy, and execution visibility. Each of the four individual micro-frameworks (Sects 3.1-3.4) contribute to each of these four areas in Fig. 8 underlying the integrity of resilience, sustainability, leagility and digitalization not only at the macro-level but also at the implementation level.

4. Discussion on implementation principles and technologies

4.1. Organizational and management implementation principles

We now discuss implementation principles and technologies for RSC. Fig. 9 illustrates a summary of the RSC organizational, technological and system perspectives.



Fig. 9. Organizational, technological and system perspectives of the RSC.

Digital SC, smart manufacturing and cloud manufacturing are becoming important determinants (Kusiak 2018, Liu et al. 2019, Rossit et al. 2019, Yang et al. 2019, Xu et al. 2019, Fragapane et al. 2020, Ivanov and Dolgui 2020). As a consequence, new disruptive SC business models arise where SCs are no more understood as a rigid physical system with a fixed and static allocation of some processes to some firms. Instead, different physical enterprises offer services in supply, manufacturing, logistics, and sales which results in the dynamic allocation of processes and dynamic SC structures. For example, electronic retailers are using their extensive transactional and behavioural customer data to offer customers new ways of trying, experiencing, and purchasing their products (e.g., Amazon with Alexa). Examples of digitalized SC and operations include logistics and control with real-time data (Park et al. 2018), dynamic resource allocation in Industry 4.0 customised assembly systems (Ivanov et al. 2016), improving forecasting models using Big Data (Johnson et al. 2016), combining optimisation, machine learning algorithms and agent-based modelling for SC resilience (Cavalcantea et al. 2019).

The RSC combines several management and organizational principles from the systems, information, organization and network theories and can be considered through the lens of these theories. The Beer's viable system model (Beer 1985) allows to understand how interconnected operations communicate with changing market environments and meta-systems such as markets, policy, and society. According to the Ashby's law of requisite variety (Ashby 1956), the situational variety should be balanced by the response variety of the controller or "only variety absorbs variety". This law can be considered as one of the RSC pillars in development of highly diversified and decentralized systems able to respond to the increasing variety in the external systems such as new market models (e.g., omnichannel), new business models (e.g., circular economy) positive disruptions (e.g., innovations) and negative disruptions (e.g., natural catastrophes) to build resilient and sustainable operational systems. Moreover, RSC poses open system context analysis. An open system (Mesarovic and Takahara 1975, Casti et al. 1979) is a system that has interactions with the environments and evolves based on these interactions. The major characteristics of *open systems* are control, self-adaptation, and self-organization (von Bertalanffy 1969, Gao et al. 2016) which can be seen as future-leading management principles for RSC.

4.2. Implementation technologies

We propose classifying the RSC implementation technologies into four areas, i.e., infrastructure, engineering technology, data technology and communication (Fig. 10).

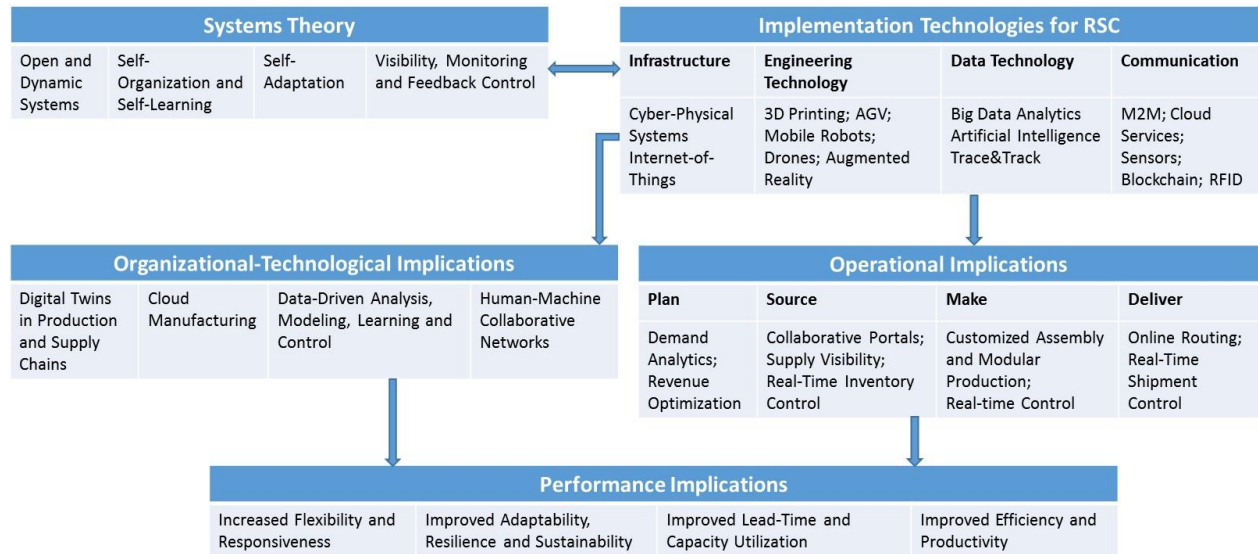


Fig. 10. Interrelations of management, technological and organizational research arrows in RSC

The individual technological contributors of the RSC (e.g., robots, sensors, agents, modular factories, Internet-of-Things (IoT), etc.) have been already known, but they were still less receptive and understood by the companies of how to use them to stay competitive. In addition, attempts to interconnect these local solutions usually failed. This became possible later, following the rapid progress in data processing and robotics technologies. Sensors, automated guided vehicles (AGV), blockchain, additive manufacturing, augmented reality, big data analytics, track&trace systems (T&T), and mobile robots are facilitating the formation of cyber-physical systems (CPS) in the SCs.

In Fig. 10, we summarize major implementation technologies, technological-organizational, operational and performance implications of RSC. We consider the RSC as a realization of some fundamental principles in the systems theory such as formation of open and dynamic systems, self-organization, self-adaptation and self-learning as well as visibility, monitoring and feedback control. Further, RSCs open new organization-technological designs such as cloud manufacturing, digital twins, data-driven modelling and collaborative industry. At the operational level, we classify the RSC implications according to the SCOR processes (plan-source-make-deliver). Finally, Fig. 10 depicts major performance implication of utilizing RSC.

4.3 Contextualization of multi-disciplinary future research directions in RSC

In this section, we offer insights on multi-disciplinary compositions of RSC research and project future research directions. Quoting Paul Valery (“*Let us enrich ourselves with our mutual differences*”) and in light with recent studies by Choi et al. (2018) and Cachon et al. (2019) that point to the necessities of multi-disciplinary research, we consider the multi-disciplinary collaboration as a key to further RSC developments in the era of Industry 4.0. Linking the further discussion to Sects. 4.1 and 4.2, we provide some conjectures of possible cross-disciplinary collaborations for some selected RSC topics.

The first observation is that interactions between human intelligence and artificial intelligence along with collaborative industry on the basis of human-machine systems belong to the future

paths in RSC developments. Comprehensively, the examinations of these topics require a multi-methodological approach complementary combining conceptual frameworks, case-studies, experiments, data-driven and model-driven decision-making support.

The second observation is that five major research areas and five major disciplines involved with RSC research can be classified as shown in Fig. 11. Management and organization, robotics and automation, artificial intelligence and data analytics, sustainability and human factors, and CPS belong to RSC research areas. The research in these areas is split across different disciplines (some exemplary connections are shown in Fig. 11 but not limited to). Obviously, the multi-disciplinary collaborations are possible and useful both within each of the research areas, and across the areas.

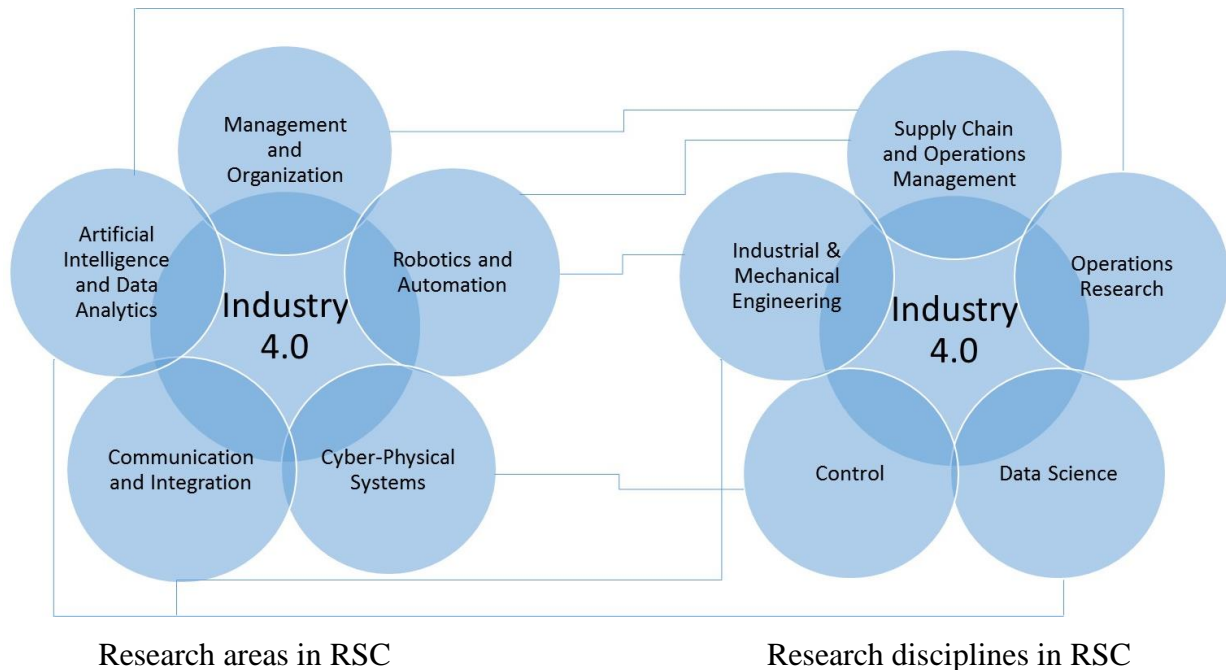


Fig. 11. Research areas and disciplines in RSC

Consider some RSC decision-making areas. Process design and production planning and control require considerations of CPS and IoT along with M2M, cloud manufacturing services and smart products. As such, a collaboration of management and engineering researchers, data science and control disciplines is needed. New production, sourcing and distribution strategies can be developed with the use of additive manufacturing, blockchain and artificial intelligence calling for a close collaboration of management researchers with industrial engineering, operations research and data science specialists.

5. Reconfigurable meta-structures and dynamic autonomous services

The frameworks derived in Sect. 3 depict some generalizable commonalities. In particular, the SC reconfiguration can be seen at the level of organizational structure (e.g., supplier base re-allocation), product structure (e.g., substitutable products), process-functional structure (i.e., customized assembly processes), financial structure (e.g., payment/contract schemes) and information structure (i.e., data storage backups).

Recent research discussed the principles and methods of SC multi-structural dynamics (Ivanov et al. 2010, Ivanov 2018b). Moreover, Ivanov et al. (2019) point out that “... *new disruptive SC business models will arise where SCs will be understood not as rigid physical systems with a fixed and static allocation of some processes to some firms. Instead, different physical firms will*

offer services of supply, manufacturing, logistics, and sales which will result in a dynamic allocation of processes and dynamic SC structures.”

Taking the X-network frameworks, the SC multi-structural dynamics concept and the service-oriented paradigms as anchors, in this study we now introduce two novel concepts within the Reconfigurable SC that operate in highly vulnerable environments – dynamic SC meta-structures and dynamic autonomous services. These two concepts are interconnected with each other (Fig. 12).

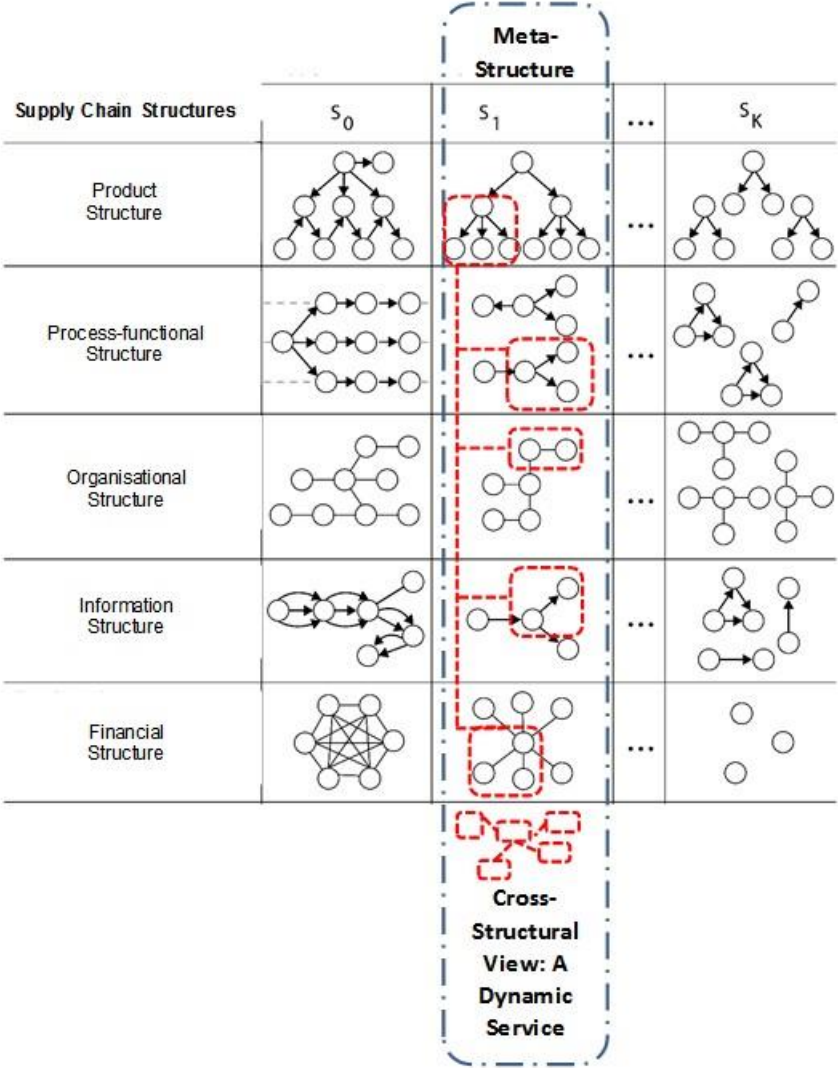


Fig. 12. Dynamic SC meta-structures and dynamic autonomous services

Fig. 12 depict the concepts of the dynamic SC meta-structures and dynamic autonomous services. A *dynamic SC meta-structure* is an integrity of all five major SC structures (i.e., organizational, product, process-functional, information and financial structures) following the results of Ivanov et al. (2010) and Ivanov (2018b). Due to changes in the individual structures, the meta-structures are dynamic and need to be reconfigurable. A *dynamic autonomous service* is a situational, cross-structural composition of the elements in different SC structures within a meta-structure. For example, in Fig. 12 we can observe a service that is offered by a collaboration of two firms (see organizational structure) which are involved with a fulfillment of three process steps / functions in order to produce / deliver a certain product output subject to certain information and financial flows.

The concepts of both the dynamic SC meta-structures and dynamic autonomous services echo the changes in traditional manufacturing and SC designs, and the resulting change in their management. These two concepts support the service-oriented paradigm SCs which are based on cyber-physical principles and digital twins (Kusiak 2019, Panetto et al. 2019, Ivanov and Dolgui 2020). Consider some examples for the structural dynamics. UPS and SAP developed a joint technology which allows UPS to manufacture items using 3D printing directly at the distribution centers (UPS 2018). As such UPS as an element of the organizational structure can flexibly change its role in the process-functional structure between the shipper and producer. IBM and Maersk are collaborating to create trust and transparency in global SCs (IBM 2018). They are developing a distributed contract collaboration platform using Blockchain technology. So the data structure in the SC is subject to dynamic reconfiguration according to the dynamics of the organizational structure. Major retailers like Wal-Mart and ALDI provide a mix of own and suppliers' substitutable products to flexibly react to demand and supply disruptions (Gupta and Ivanov 2020).

These and other examples allow for the new proposition that new objects for management and control – the dynamic autonomous SC services – are currently being formed (Fig. 13).



Fig. 13. Concept of a dynamic autonomous SC service

The services can be understood as a virtual object that contains an organization unit (e.g., an assembly line) or a combination of units (e.g., a buyer-supplier relationship), process and function (e.g., a certain assembly step in a customized manufacturing process), product(s) involved with the execution of the process/function, and coordination mechanism in terms of data and financial flows. As such, the management of the suppliers, products, processes, information and transactions is integrated within the concept of the dynamic autonomous service. The key idea is situational, reconfigurable networking of services. Notably, this study posits the novel concepts of the SC meta-structures and dynamic services as generalized constructs that require a specific analysis and detailization in concrete application environments.

Consider a formal description of the dynamic SC meta-structures and dynamic autonomous services using the structure dynamics control theory (Ivanov et al. 2010) and dynamic interpretation of operations execution in the SC (Ivanov and Sokolov 2012). The meta-structural states can be defined as a set of different structures $G = \{G_\chi, \chi \in W\}$, where W is a set of alternative structures. Since the structures are changing in time, we use the dynamic alternative multi-graph (1) to describe the meta-structural dynamics:

$$G_\chi^t = \langle X_\chi^t, F_\chi^t, Z_\chi^t \rangle, \quad (1)$$

where the subscript χ characterizes the SC structure alternative; the time point t belongs to a

given set T ; $X_\chi^t = \{x_{<\chi>}^t, \chi \in L_\chi\}$ is a set of elements of the structure G_χ^t (the set of dynamic alternative multi-graph nodes, e.g., suppliers) at the time point t ; $F_\chi^t = \{f_{<\chi,l,l'>}^t, l, l' \in L_\chi\}$ is the set of arcs of the dynamic alternative multi-graph; G_χ^t represents available transportation channels at time t ; and $Z_\chi^t = \{z_{<\chi,l,l'>}^t, l, l' \in L_\chi\}$ is a set of SC parameters such as capacity and inventory.

A SC meta-structural state can be defined as the inclusion (2):

$$S_\delta \subseteq X_1^t \times X_2^t \times X_3^t \times X_4^t \times X_5^t, \delta = 1, \dots, K_\sigma. \quad (2)$$

Now we obtain the set of the structural states (3):

$$S = \{S_\delta\} = \{S_1, \dots, S_{K_\sigma}\}. \quad (3)$$

The meta-structural dynamics can be expressed by maps, as shown in (4):

$$\Pi_{<\delta,\delta'>}^t : S_\delta \rightarrow S_{\delta'}. \quad (4)$$

Assuming that the meta-structural states at time $t \in T$ can be defined by a composition (3), the SC meta-structural dynamics can be modelled as the selection of structural states $S_\delta^* \in \{S_1, S_2, \dots, S_{K_\sigma}\}$

and transition sequences using composition

$$\Pi_{<\delta_1,\delta_2>}^{t_1} \circ \Pi_{<\delta_2,\delta_3>}^{t_2} \circ \dots \circ \Pi_{<\delta',\delta>}^{T_f}$$

under the optimization of some performance criteria, e.g. annual sales or customer service levels.

For the formal description of the dynamic autonomous services, we introduces a set $A = \{A_i, i = 1, \dots, n\}$ of n -customer orders (this set refers to the product structure), a set $M = \{M_j, j = 1, \dots, m\}$ of m -companies in the SC (this set refers to the organizational structure); a set $D^{(i)} = \{D_\kappa^{(i)}, \kappa = 1, \dots, S_i\}$ of operations which can be executed in the SC, where S_i is the total number of the operations that a SC can realize (this set refers to the process-functional structure), and a set $P^{(i)} = \{P_\kappa^{(i)}, \kappa = 1, \dots, S_i\}$ of material, energy, finance and information flows in the SC which represent the respective resources and their consumption required for production of different jobs (this set refers to financial, information and process-functional structures).

An intersection of the sets A , M , D , and P is a *dynamic autonomous service*; i.e., an entity needed to fulfill a value-adding process step. The services are formed dynamically based on the changing customer demands and availability of resources in the SC. We refer to the models of SC dynamics using the service-oriented approach in the studies (Ivanov et al. 2014, 2020).

6. Future research directions

Supply chain management has evolved a lot for the last decade: new research areas have been established and new research methodologies have been adopted. Some of them seem to be incremental, yielding a fragmented community. Others point to expanded diversity and the new areas of research that opened up. Obviously, neither group is entirely wrong, nor entirely correct. Un-

doubtedly, a growing set of domains has becoming included into the SC management and research using different tools from management, operations research, industrial engineering and computer science (Fig. 14).

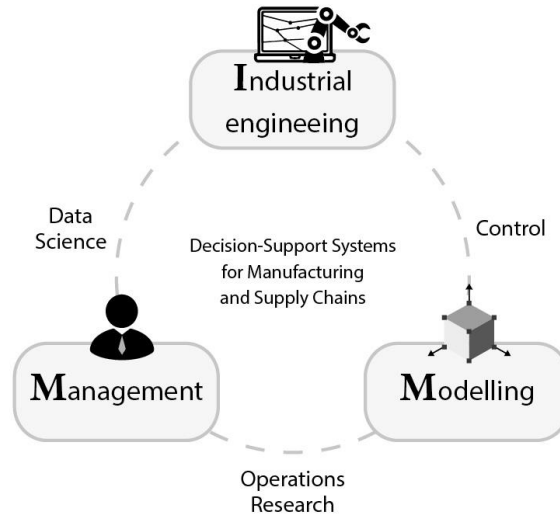


Fig. 14. Interdisciplinary research agenda in SC management

Fragmentation and isolated methodical views are symptomatically problematic. To get out of their ruts, to have greater impact, the SC field needs to ask questions that are important in real context and provide answers that are utilizing the technology used in real world. At the same time, SC research community needs to think proactively and elaborate on new paradigms, methods, principles to develop the SC domain further.

In particular, this study tried to avoid the trap of specificity and expand our horizon beyond (relatively) isolated fields within the SC management in order to connect and actively engage with diverse audiences. In this section, we organize the debate around several future research topics that can be considered within the RSC frameworks.

6.1 Meta-structures and dynamic autonomous services

One major driver in the discussion about the new principles in SC management and engineering is the changeability / reconfigurability of the SC structures. Numerous practical and theoretical developments of recent years confirm the assumptions that the SC are transforming from the physical systems with a fixed and static allocation of some processes/products/data to some firms towards dynamic reconfigurable services which are composed of different elements across the different, dynamically changing structures. In early 2000s, the ideas of dynamic SC formations have found first developments in the area of virtual enterprises and collaborative networks (Ivanov et al. 2004, 2005, Camarinha-Matos and Afsarmanesh 2005, Sarkis et al. 2007, Ivanov et al. 2009, Ivanov and Sokolov 2012). Other relevant research streams can be found in the theories of complex adaptive systems (Choi et al. 2001, Surana et al. 2005, Nair and Reed-Tsochas 2019) and SC structural dynamics (Ivanov et al. 2010). The RSC framework proposed can provide new threads in progressing the ideas of dynamic SC formations.

6.2 Digital twins

Recent research theorized a notion of digital SC twins – computerized models that represents the network state for any given moment in real time (Ivanov and Dolgui 2020). We explore the conditions surrounding the design and implementation of the digital twins when managing disruption risks in SCs. The proposed conceptual framework of a digital twin for SC disruption management

is rooted in a combination of model-based and data-driven approaches. This combination allows uncovering the interrelations of risk data, disruption modeling, and performance assessment. The framework developed, for the first time, conceptualizes the digital SC twin and advances our understanding about *when* and *how* to integrate data analytics into manage SC disruption risks towards building a theory of a digital SC. The findings presented can also guide firms in properly maintaining data for disruption risk management and highlight potentials of transition from offline to online decision-making support. The results of this study contribute to the research and practice of SC risk management by enhancing the researchers' and decision-makers' understanding for predictive and reactive decisions by utilizing the advantages of SC visualization, historical disruption data analysis, and real-time disruption data to ensure end-to-end visibility and business continuity in global companies.

6.3 Resilience

Two important issues of SC reconfigurability are efficiency and resilience which are dependent on the certainty of our knowledge about the environment and its changes. The unpredictability of the occurrence of disruptions and their magnitude suggests that designing SCs with a low need for "certainty" may be as important, if not more so, than predetermined disruption control strategies. In this setting, a new research perspective in SC management, i.e., low-certainty-need (LCN) SCs has recently been opened (Ivanov and Dolgui 2019). Structural variety, process flexibility, and parametrical redundancy are identified as key LCN SC characteristics that ensure efficient disruption resistance as well as recovery resource allocation. Two efficiency capabilities of the LCN SC are shown, i.e., low need for uncertainty consideration in planning decisions and low need for recovery coordination efforts based on a combination of lean and resilient elements. New developments in artificial intelligence, business analytics and smart manufacturing could extend the scope of LCN framework and implementation tools.

6.4 Ripple effect

Disruption propagation, i.e., the ripple effect in SCs is another promising research direction (Dolgui et al. 2018). What are the SC design structures that are more prone to the ripple effect? How to control the ripple effect with an efficient, sustainable resource utilization? How to make use of available digital technology to improve resilience and mitigate the ripple effect. These and other questions require an interdisciplinary analysis combining the views of resilience, sustainability, digitalization and leagility.

6.5 Value webs

When analyzing the current and future trends in SC management, we offer a conjecture that SCs evolve towards value webs that are characterized by structural dynamics. Ivanov (2020) shows that differently than the traditional, linearly directed SCs with static structures, the firms in value webs may exhibit multiple behaviors by changing the buyer-supplier roles in interconnected or even competing SCs and causing dependence asymmetry (Dong et al. 2015). For example, a competitor of a focal firm can also serve as the focal firm's upstream supplier playing the role of both supplier and competing focal firm in two different but intersecting SCs simultaneously as discussed in Zhao et al. (2019). Fracassia et al. (2017) point to the multiple, intersecting SCs in the industrial symbiosis that are characterized by using the waste of some SC processes as the inputs into the other SCs. Choi et al. (2020) show different forms of SC interconnections in the sharing and circular economies. As such, we can conclude that many SCs evolve into value webs based on the principles of co-creation and co-evolution (Brintrup et al. 2015, Demirel et al. 2019).

Such mechanisms are principally aligned with the RSC framework which can be used for further progressing the state-of-the-art and offering new practical applications in research on value webs.

7. Conclusion

Although digitalization, resilience, sustainability and leagility have evolved from emergent topics to major determinants in the SC management and research, attention has been yet mostly focused towards their individual contributions to the firm's profitability and competitiveness. A conceptual guidance surrounding their roles and interplays as an integrity was missing. Our study aims at contributing to close this research gap. Utilizing a methodology based upon an abductive approach, systematic bibliometric co-occurrence analysis of 1383 articles and tertiary studies towards a conceptual theory building, we show how digitalization, resilience, sustainability and leagility can be positioned self-contained in their singularity and mutually enhanced by each other in their integrity within the Reconfigurable Supply Chain (RSC).

We proposed respective frameworks, the implementation technologies and principles at the macro and micro levels towards a conceptual theory building which results into the introduction of two novel concepts within the RSC that operate in highly vulnerable environments – dynamic SC meta-structures and dynamic autonomous services.

Moreover, we offered several potential future research directions which can be progressed using the RSC paradigm. These are: SC meta-structures and dynamic autonomous services, digital SC twins, SC resilience, the Ripple effect, and value webs.

The outcomes of this research can be used to advance the researchers' perspectives on the future developments in the SC management theory under the 3P Triade: People, Planet, Profit. Most importantly, with the results presented we go beyond the existing knowledge and proactively predict the promising directions in future of RSC research. Alike our results can be of value for decision-makers to decipher systematically the chances and barriers in the contemporary SC transformations.

Some limitations exist in this paper, as with any study. We took a much generalized, "bird-eye" perspective on the SC reconfigurability. For concrete applications, the RSC concept and the RSC modelling should be detailed and extended given the context of decision-making situations. In addition, the RSCs themselves need to be thoroughly investigated in terms of methodology and practice of their formations and control. Mathematical modelling approaches for RSC present a vast array for further investigations. These areas but not limited to can be considered promising future research avenues.

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